Current FEL Physics Research at SLAC

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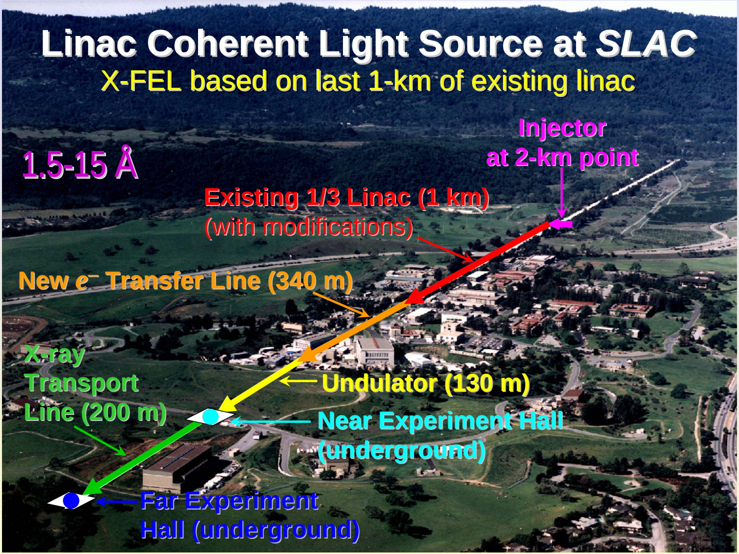
Outline of the talk

The main theme of this talk is research at SLAC aimed at improving coherence properties of FEL radiation.

- LCLS at SLAC
- SASE and FEL coherence
- Echo-Enabled Harmonic Generation (EEHG)
- Self-seeding at LCLS
- Toward TW FEL
- Noise suppression
- LCLS upgrade: LCLS-II
- Conclusions

Linac Coherent Light Source at SLAC



Linac Coherent Light Source at SLAC

LCLS FEL Parameters

- Electron beam energy 3.5-13.6 GeV, peak current up to 3.5 kA, slice emittance 0.4 μm
- Photon energy 480 eV - 10 keV
- Pulse energy up to 4 mJ with nominal beam charge 0.25 nC.
- Peak FEL power up to 30 GW
- Pulse length 70 - 300 fs FWHM (or even shorter than 70 fs)
- Peak brightness (at hard x-rays) 2×10^{33} $s^{-1}mm^{-2}mrad^{-2}$ per 0.1% spectral bandwidth - 10 orders of magnitude jump in peak brightness!

P. Emma et al., Nature Photonics, **4**, *641 (2010).*

Coherence properties of the FEL radiation

The SASE (Self Amplified Spontaneous Emission) radiation starts from initial shot noise in the beam, with the resulting radiation having . . .

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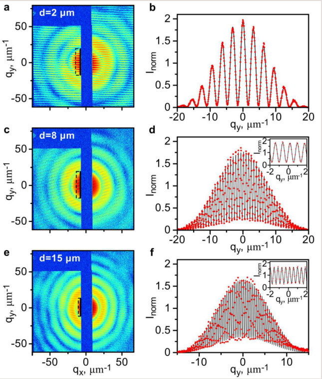

PRL 107, 144801 (2011)

an excellent spatial coherence, ...

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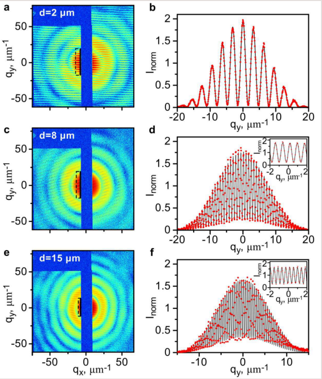

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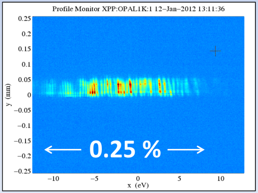
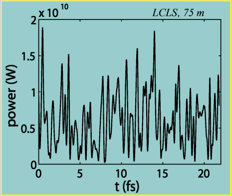


Measured SASE spectrum at LCLS



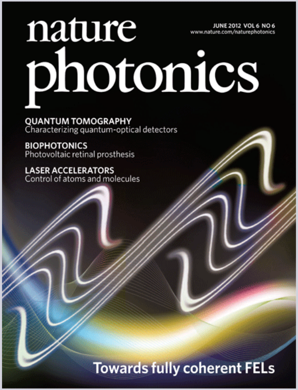
Simulated power vs time for LCLS

but a rather poor temporal one.

an excellent spatial coherence, . . .

Improving longitudinal coherence properties

Improving longtigudinal coherence of modern FELs is an important area of research at SLAC, and worldwide.



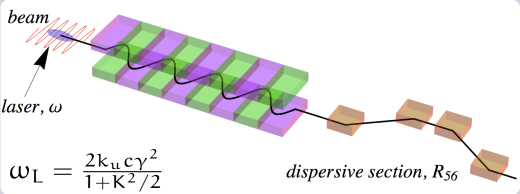
There are several approaches to generation of longitudinally coherent FEL radiation based on seeding techniques

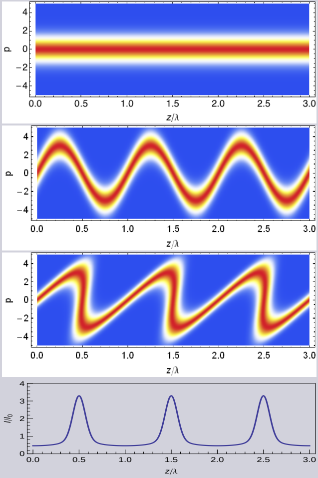
- High Harmonic Generation (HHG)
- High-Gain Harmonic Generation (HGHG)
- Echo-Enabled Harmonic Generation (EEHG)
- Self seeding (hard and soft x-rays)

SLAC is involved in development of the last two.

HGHG seeding

HGHG modulates the FEL bunch current at a harmonic of the laser frequency (L. H. Yu, 1991).

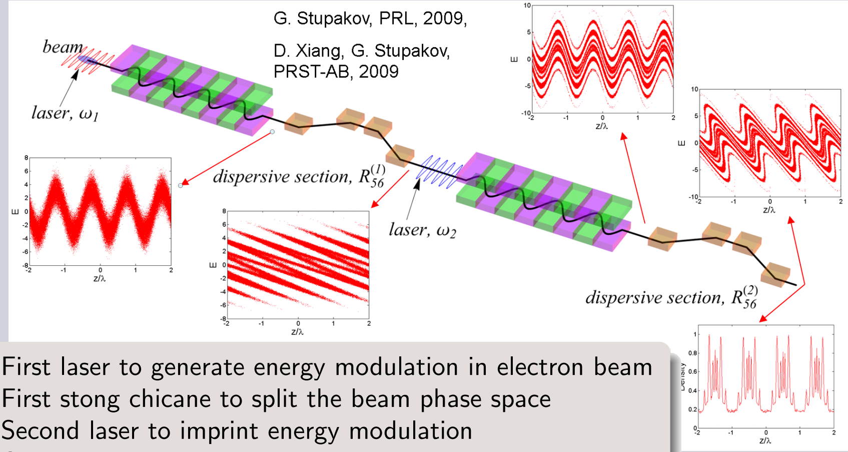




The laser-beam interaction in the undulator generates energy modulation in the beam at the laser wavelength. The maximal harmonic number in HGHG increases with the amplitude of the energy modulation of the beam, $n \propto \Delta E_{mod}$, however large E_{mod} deteriorates the lasing properties of the beam. In practice, one can rely on $n \approx 10$. Higher harmonic numbers require several stages of the seeding (FERMI FEL at Trieste).

Using echo effect for high-frequency modulation

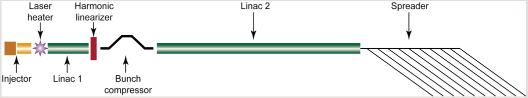
EEHG uses a strong dispersion element in the first modulator and add one more modulator-chicane (radiator-undulator is not shown).



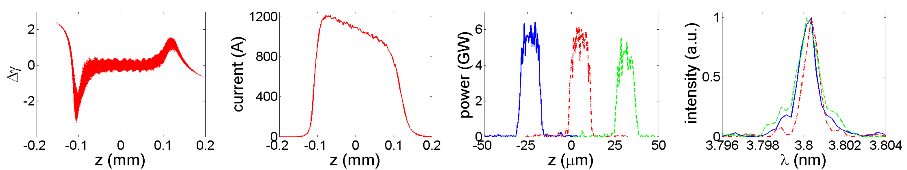
- First laser to generate energy modulation in electron beam
- First stong chicane to split the beam phase space
- Second laser to imprint energy modulation
- Second chicane to convert energy modulation into density modulation

LBNL soft x-ray FEL (NGLS)

Main parameters:
Beam energy 2.4 GeV
Energy spread: 100 keV
Emittance: 0.7 mm mrad
Peak current: 1 kA

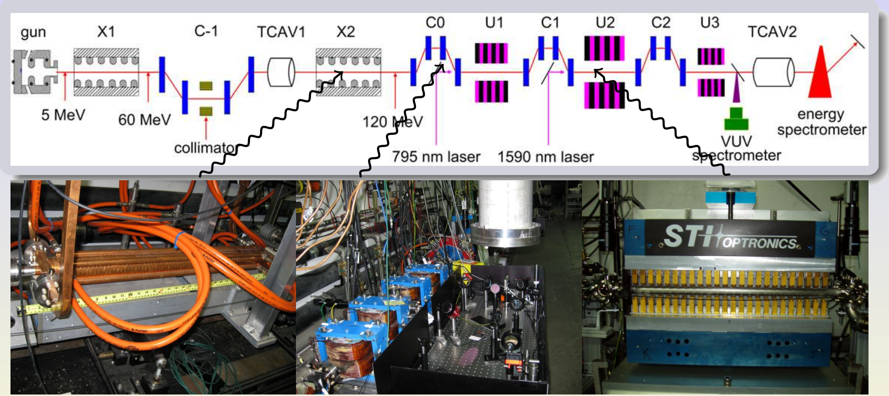


EEHG is currently considered as one of the seeding options for this project.



The beam distribution is obtained from IMPACT-Z (J. Qiang). Radiation at 3.8 nm (50th harmonic of 190 nm laser) with the spectrum close to the Fourier limit (GENESIS simulations). The output pulse length is about 12 fs (rms) and the relative spectral bandwidth is 2.7×10^{-4}, about 1.3 times larger than the Fourier transform limit. The power saturates after 7 undulator sections with the length of 2.4 m each.

EEHG proof-of-principle experiment at SLAC



A proof-of-principle experiment to demonstrate EEHG has been carried out at SLAC at the NLCTA facility (Xiang et al., PRL, 2010). NLCTA is equipped with an S-band injector (up to ~ 100 pC), an X-band linac ($60 - 200$ MeV) and Ti:Sapphire laser systems.

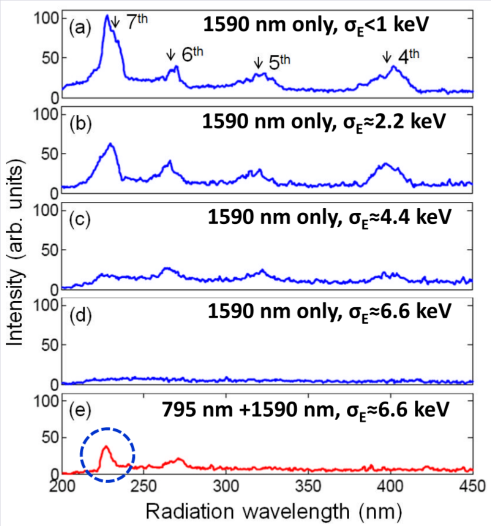
ECHO-7@NLCTA at SLAC

Parameters of the experiment:

Electron beam energy	120 MeV
Bunch length	0.5-2.5 ps
Bunch charge	20-40 pC
Normalized emittance	~ 8 µm
Slice energy spread	~ 1 keV
First laser wavelength	795 nm
Second laser wavelength	1590 nm
Peak energy modulation in U1 and U2	10-40 keV
R_{56} for C1 and C2	1-9 mm

The slice energy spread in the beam can be increased by raising the voltage at TCAV1 rf structure.

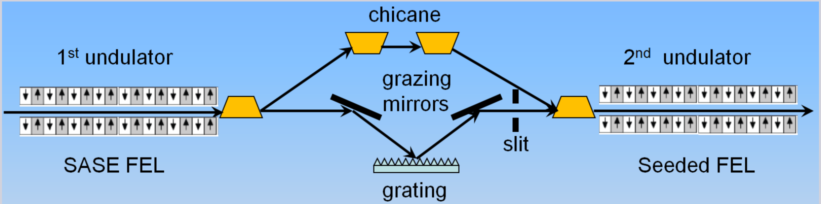
EEHG 7th harmonic



EEHG at 7th harmonic of the second laser was demonstrate in 2011 (Xiang et al., PRL, 2012).

Spectrum of the radiation for various beam slice energy spreads. The beam slice energy spreads are varied by changing TCAV voltages. (a)(d) are the HGHG signals when only the 1590 nm laser is on, and (e) is the EEHG signal with both lasers on.

Self-seeding if FELs

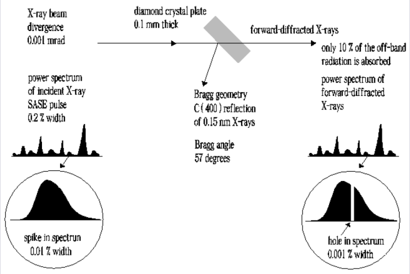


- First undulator generates SASE
- X-ray monochromator filters SASE and generates the seed
- Chicane delays electrons and washes out SASE microbunching
- Second undulator amplifies the seed to saturation

J. Feldhaus et al., NIMA, 1997.
E. Saldin et al., NIMA, 2001.

Hard x-ray self seeding

The problem: long x-ray path delay (~10 ps) requires large chicane that takes space and may degrade beam quality. A great idea to overcome this difficulty: G. Geloni, V. Kocharyan and E. Saldin, DESY 10-133 (2010).



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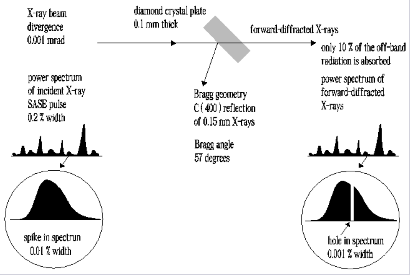

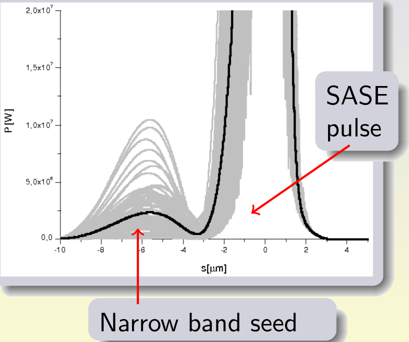

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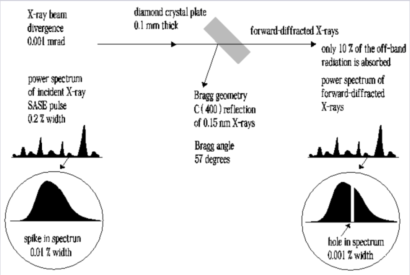
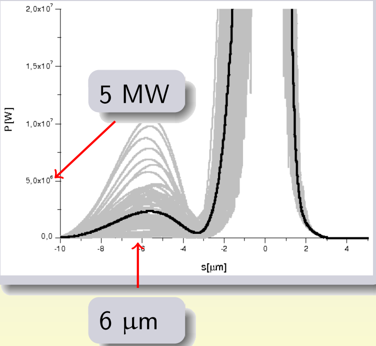
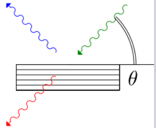
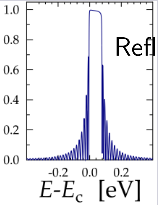




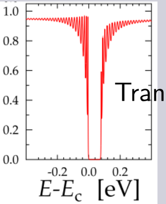
Detailed theory of forward Bragg diffraction

Detailed theory is developed by R. Lindberg and Yu. Shvyd'ko (PRST-AB, 2012). Diamond crystal, C(004), $\theta = 45^\circ$, $E_C = 9.8$ keV.

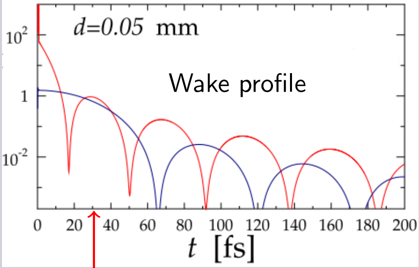




Reflection



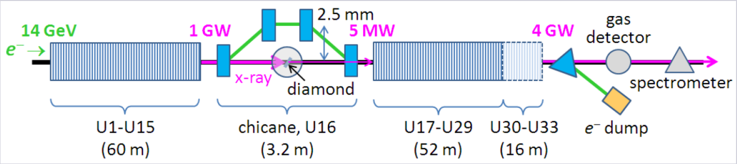
Transmission



Wake profile

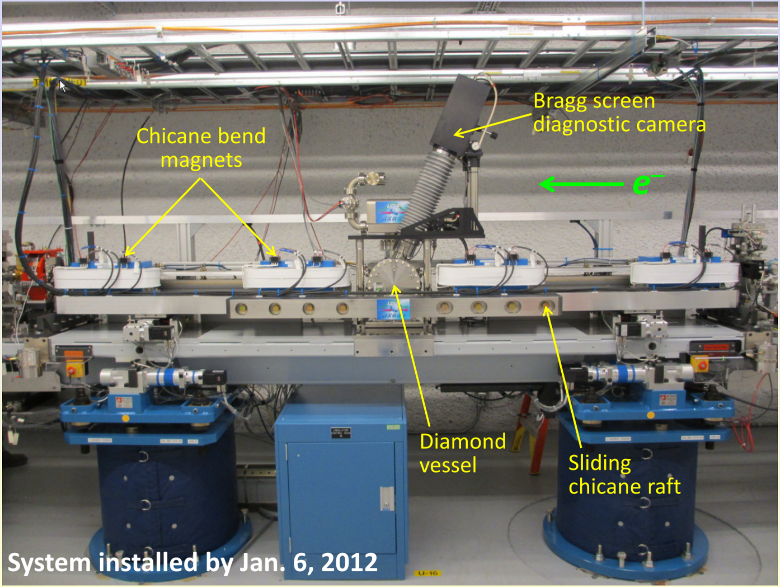
Beam goes to here

Self seeding at LCLS:

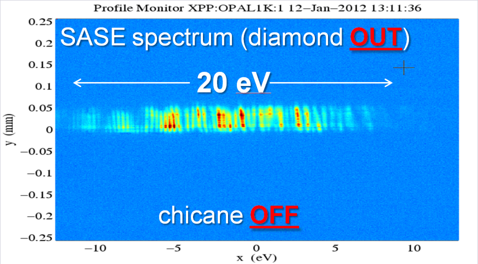


The monochromator crystal is 110-μm thick with a total area of 4.5 mm × 4.0 mm. The diamond crystal was grown at the Technological Institute for Super-hard and Novel Carbon Materials (TISNCM, Troitsk). The required peak x-ray power at the input to the monochromator, needed to seed the FEL, is ∼ 1 GW. The magnetic chicane displaces the electrons horizontally 2.5 mm in order to bypass the diamond. This also delays the electrons by up to 40 fs in order to overlap the delayed monochromatic x-ray seed pulse.

Self seeding at LCLS



Self seeding at LCLS: results



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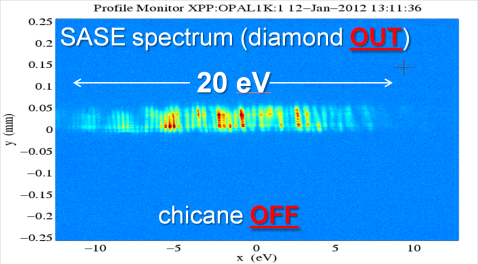

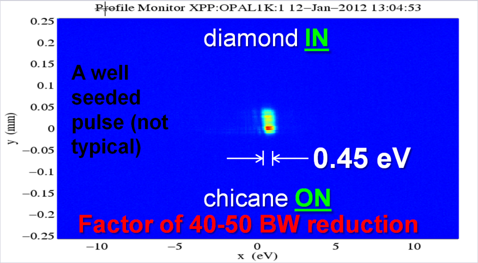

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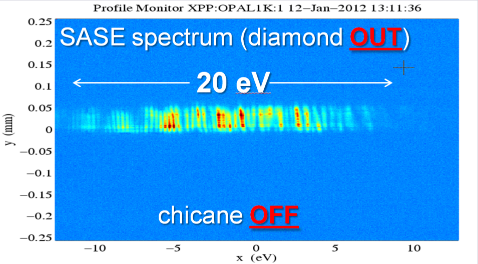
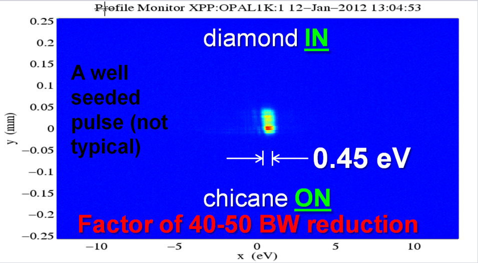
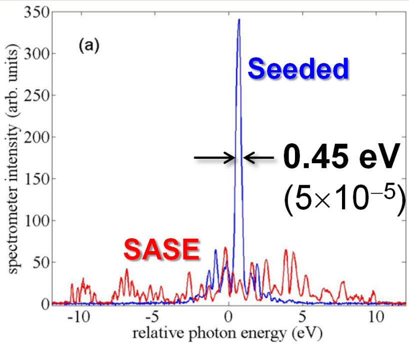


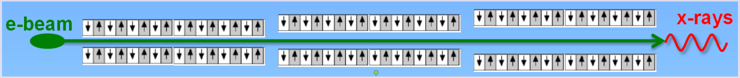




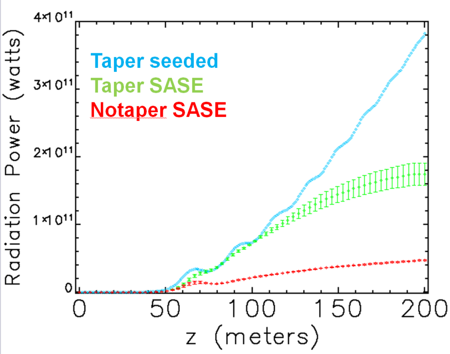
Fourier transform limit is 5 fs, (Amman et al., Nature Photon., (2012)).

Undulator tapering to enhance FEL efficiency

- FEL saturates due to significant energy loss of beam particles, $\lambda_r = (\lambda_u/2\gamma^2)(1 + K^2/2)$
- Tapered undulator keeps FEL resonance and increase power



- Taper works much better for a seeded FEL than SASE

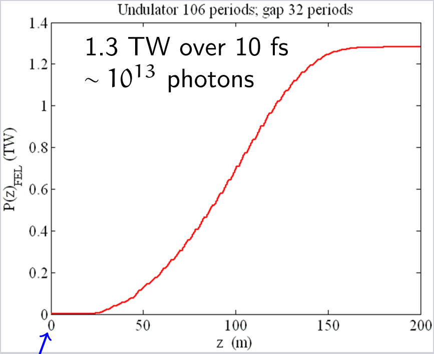


W. Fawley et al., NIMA (2002), simulations for hard x-ray LCLS.

TW FEL - LCLS-II simulations

W. Fawley, et al. FEL2011.

- LCLS-II simulation
- 8.3 keV – 1.5 Å (13.64 GeV)
- 4 kA, 0.3 μm emittance
- LCLS low charge parameters
- Optimized tapering starts at 16 m with K decreasing to 200 m



After self-seeding crystal

TW FEL - LCLS-II simulations

W. Fawley, et al. FEL2011.

- LCLS-II simulation
- 8.3 keV – 1.5 Å (13.64 GeV)
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- LCLS low charge parameters
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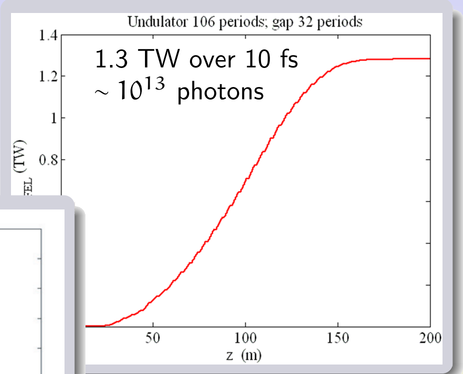
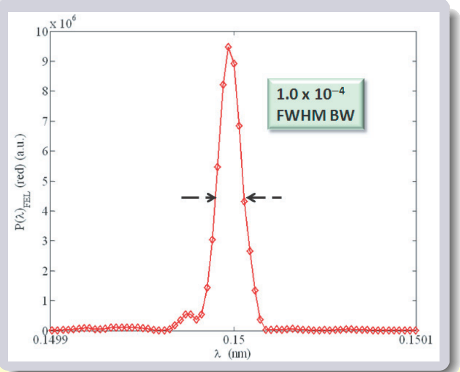


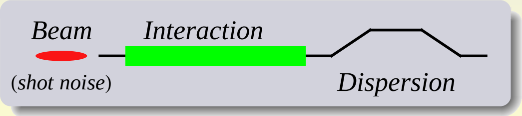


Noise reduction in relativistic beams

Noise suppression in relativistic beams was proposed by Gover and Dyunin, (PRL, 2009), Litvinenko (FEL 2009), Ratner et al., (PRSTAB 2010). Possible applications include: suppression of the fundamental harmonic in favor of higher harmonics in FELs; noise suppression for seeding; application in collective electron cooling.

The general idea is known from 1950s from RF sources—after a quarter of plasma oscillations in an electron beam the shot noise is reduced.

A simple model which can be solved analytically (Ratner, Huang and Stupakov): beam particles interact via Coulomb forces in a straight region and then pass through a chicane. The beam initially is assumed to have shot noise (uncorrelated positions of particles).



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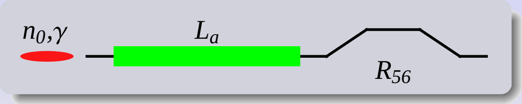


The form-factor which determines radiation of the beam at wavelength $2\pi/k$ after the dispersive section

$$F = \frac{1}{N}\sum_{j,l} e^{ik(z_j - z_l)} = (1 - \Upsilon)^2$$

with

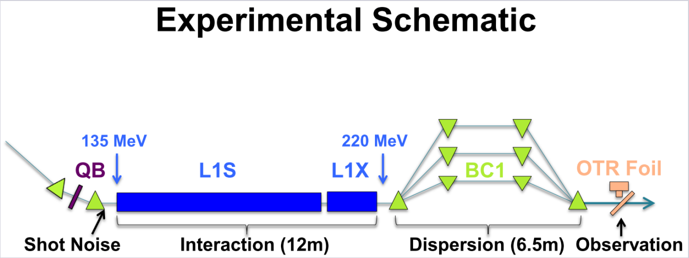
$$\Upsilon = n_0 R_{56} \frac{4\pi r_e L_a}{S\gamma}$$

n_0 - number of particles per unit length, S - beam transverse area, L_a - length of interaction region.

For shot noise $F = 1$, incoherent radiation. With $F < 1$ radiation is smaller than the incoherent radiation.

Experiment at LCLS

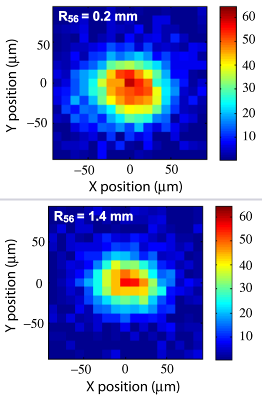
First experimental demonstration at shot noise suppression at optical frequencies, Ratner, Stupakov (PRL, 2012).

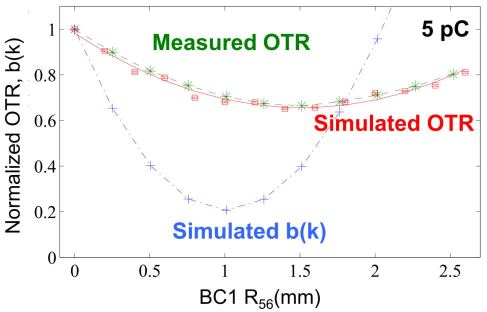


The OTR signal was observed after the BC1 chicane (no energy chirp was introduced in the beam). The intensity was measured as a function of R_{56} of the chicane. We expect a quadratic dependence of intensity of OTR versus R_{56}.

Noise suppression and experiment at LCLS

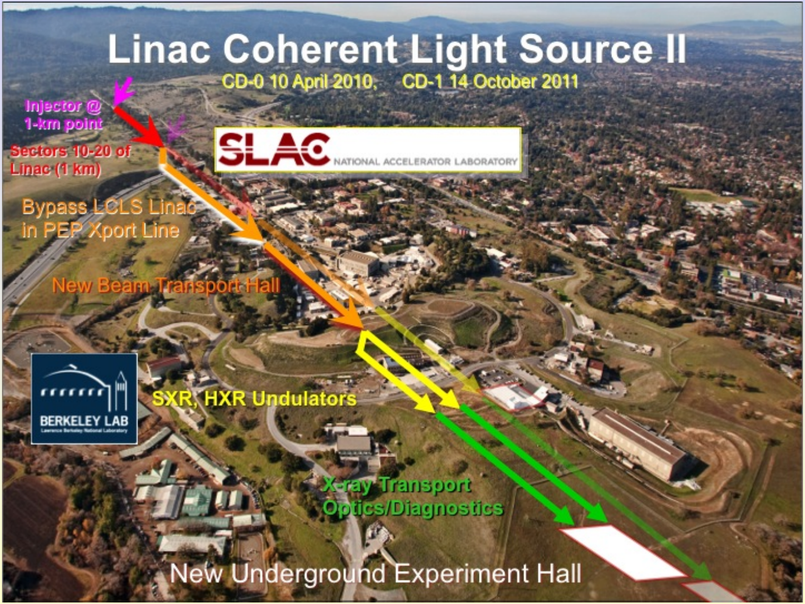
It is important to establish uncorrelated noise condition in the beam at the entrance to the system.
Beam image without noise suppression (top) and with (bottom).



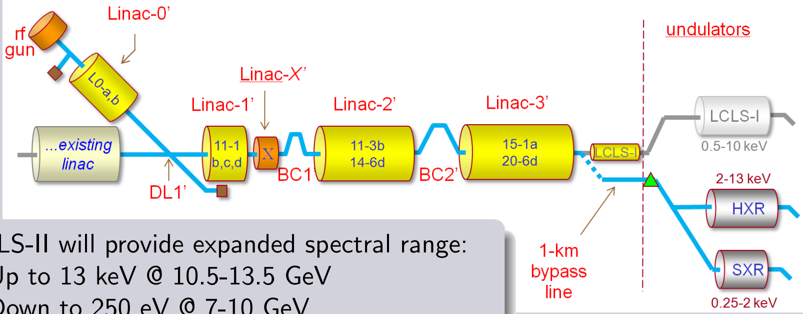


Comparison of the experiment with simulations. One fitting parameter was used.

Future: LCLS-II at SLAC



LCLS-II -Enhanced Capability and Greater Capacity



LCLS-II will provide expanded spectral range:

- Up to 13 keV @ 10.5-13.5 GeV
- Down to 250 eV @ 7-10 GeV
- 302m undulator tunnel

- Adequate space to accommodate future enhancements:
- Seeding
- Polarization control
- TW peak power
- Two new SASE undulator x-ray sources, both variable gap

Conclusions

- SLAC is actively involved in research aimed at drastic improvement of the longitudinal coherence of SASE FELs. The directions that are currently pursued include self-seeding for hard (and soft) x-rays and echo-enabled harmonic generation for soft x-rays.
- Using undulator tapering, a seeded FEL can achieve much higher output power, reaching the terawatt region.
- Noise suppression in relativistic beams is a promising approach which, if successful, might further improve performance of future FELs. Proof of principle experiments at optical frequencies were recently carried out at LCLS.
- The LCLS upgrade, LCLS-II, will incorporate the latest developments of the current FEL research.

Acknowledgments

Thanks to my collaborators at SLAC D. Xiang, Z. Huang and D. Ratner.